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GB 0856109 GB 0751256 US 4427908

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H2A

(54) A method for controlling the loadability of high speed air-cooled turbo-alternators and an arrangement for carrying out the method

(57) A method for controlling the loadability of high speed air-cooled turbo-alternators (10), in which the rotor winding has an intensive direct conductor cooling, and when the load increases, the pressure of the cooling air is increased at most up to 2 bar abs., while with decreasing load said pressure is decreased till the atmospheric value is reached and during the pressure adjustment the temperature of the rotor winding is kept substantially unchanged.

An arrangement for carrying out the method comprises an air-recirculating cooling system (11, 12, 13, 14) and an air supply means (17) with a compressor (22, 23) and an air tank (20) and in the arrangement a pressure adjusting means (18 and 19) is provided capable of continuously changing the pressure in the interior within a range of about 1.01 and 2 bar abs.

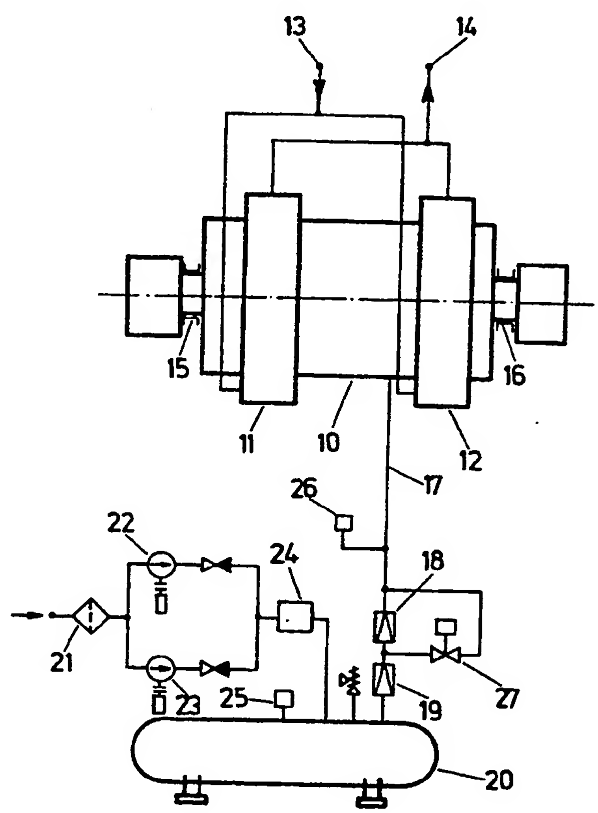

Fig. 3

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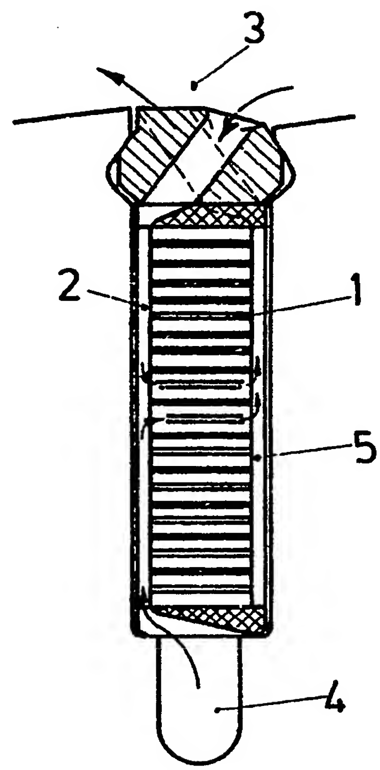


Fig. 1

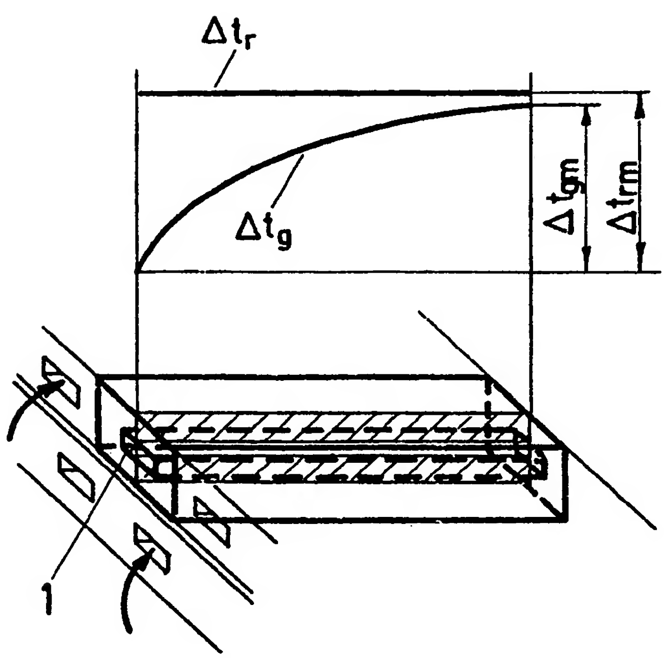


Fig. 2

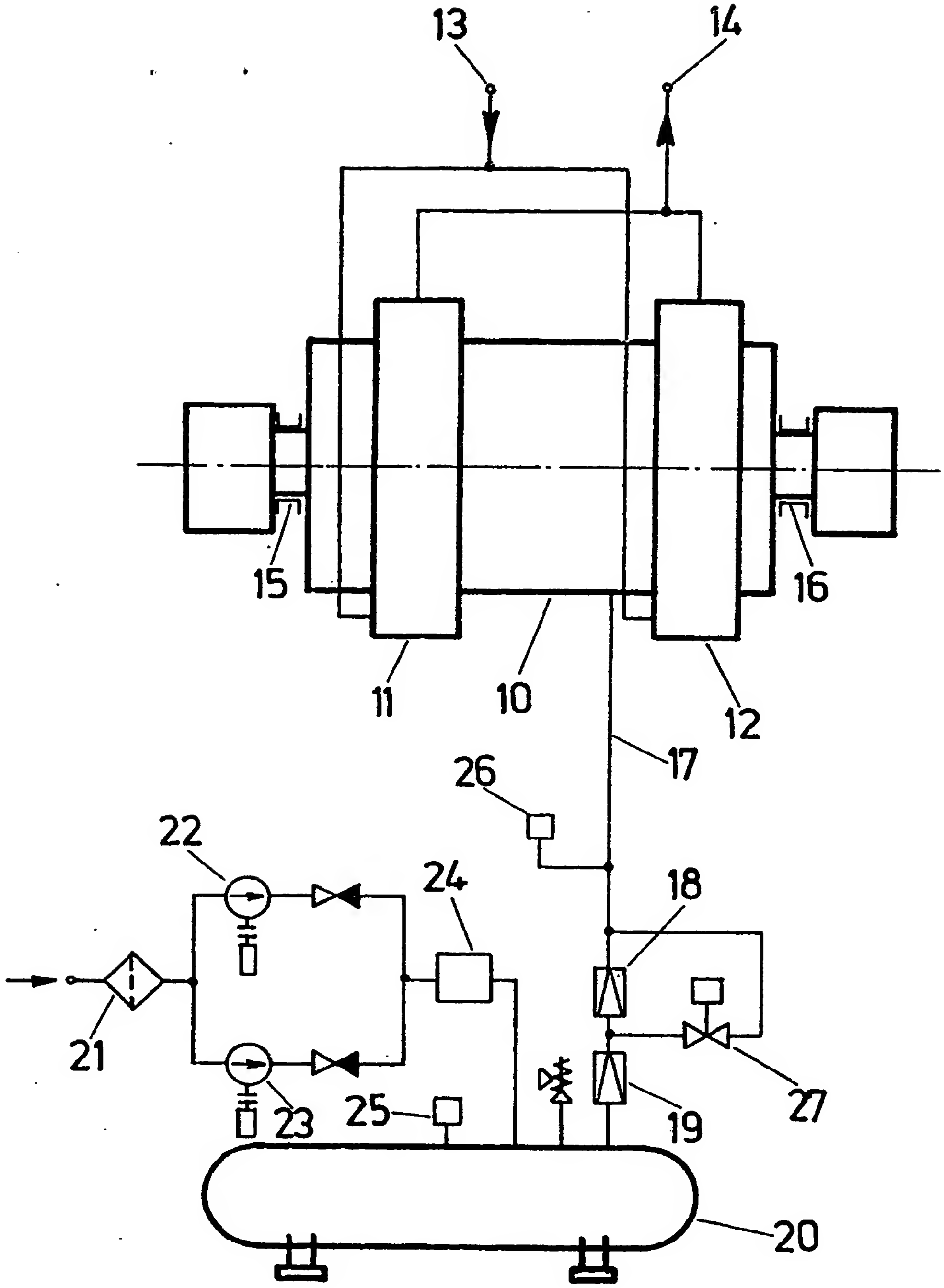
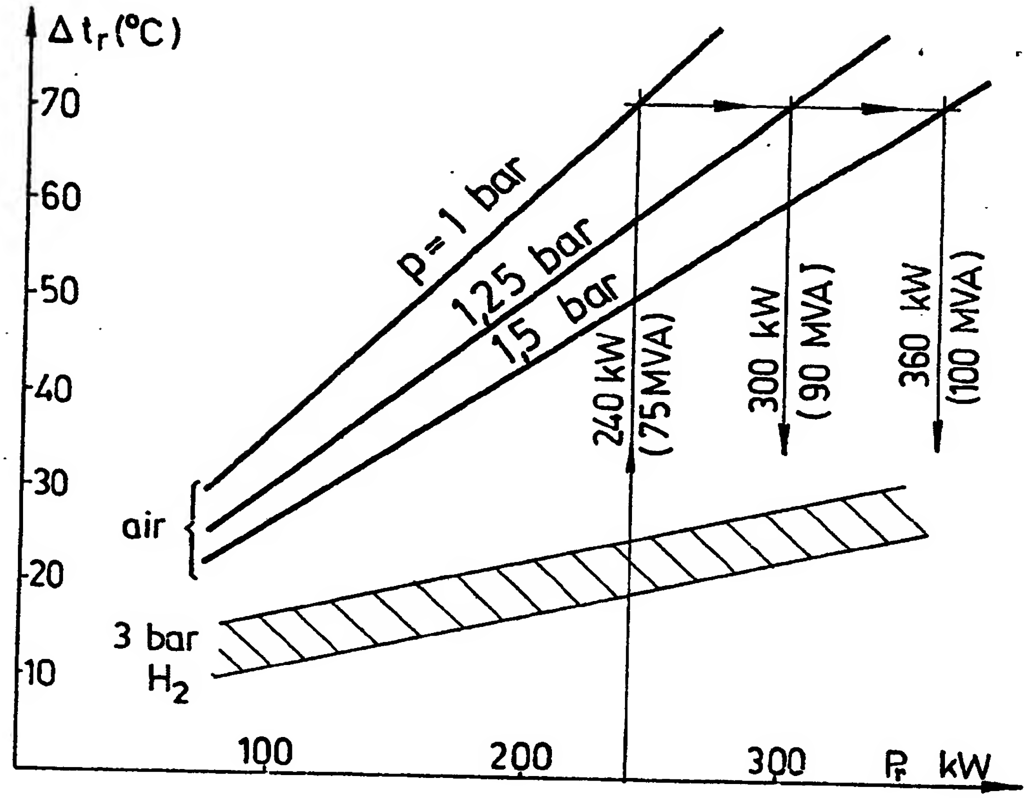
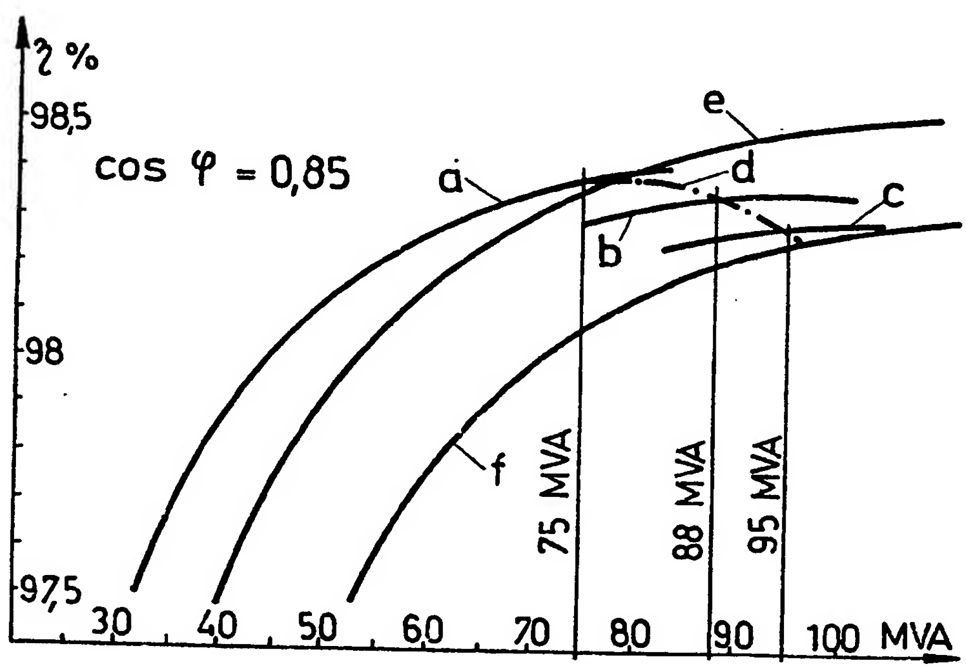


Fig. 3



Δ t_r (°C)
70
60
50
40
30
20
10
p=1 bar
1,25 bar
1,5 bar
air
3 bar
H2
240 kW (75 MVA)
300 kW (90 MVA)
360 kW (100 MVA)
100
200
300
Pr kW

Fig. 4



η %
98,5
98
97,5
cos φ = 0,85
a
b
c
d
e
f
75 MVA
88 MVA
95 MVA
30
40
50
60
70
80
90
100 MVA

Fig. 5

SPECIFICATION

A method for controlling the loadability of high speed air-cooled turbo-alterntors and an arrangement for carrying out the method

The invention relates to a method for controlling the loadability of high speed air-cooled turbo-alternators and to an arrangement for carrying out the method.

It is well known in the art that the loadability of high speed air-cooled turbo-alterantors i.e. synchronous generators with 2 or 4 poles, is defined basically by the warming up of the rotor winding through which DC currents are flowing. In the case of indirect cooling the winding is embedded in insulating material, and the loss-heat streams under the effect of existing temperature differences through the insulating material and the surrounding core material towards the heat dissipating surface formed by the mantle surface of the rotor, wherein this loss-heat is transferred via a surface temperature drop to the cooling air streaming in the air gap of the machine. The temperature of the winding is defined by the sum of the warming up of the cooling air and the resulting value of the individual temperature drops through the heat passage route.

A known way of obtaining an intensified cooling is the direct cooling of the conductors, in which a cooling air introduced in an appropriate way in the interior of the rotor gets in direct contact with the coil material which requires cooling. In this way a major portion of the temperature drops required in the indirect cooling for transferring the loss-heat to the cooling medium will cease to exist and the temperature of the conductor will be just by the value of the surface temperature drop above the warming up of the cooling medium. In this way, if the same upper temperature limit defined by the heat enduring properties of the insulating materials is considered in both ways of cooling, then in the case of the direct conductor cooling higher loss-heat can be dissipated i.e. the machine can be run with a higher load.

There are many conventional ways of directly cooling the rotor winding. In a preferable type of such cooling the rotor winding is designed in such a way that from the point of view of the streaming of the cooling air the winding can be considered as a plurality of parallel short channels with walls through which electrical current is flowing. The cooling gas can be supplied to such a winding in a known way through the air gap and this kind is often referred to as cross-channel pick-up supply. Such kind of cooling is disclosed in the paper of P. Asztalos "Direct Cooling Systems for Turboalternator Rotors in view of the Maximum Rating of Hydrogen Cooling" in page 1936 viz. Figs. 1 to 3 (IEEE Transactions of Power Apparatus and Systems, Vol. PAS–89, No. 8, 1970. pp. 1935–1945).

In an alternative way of cooling the cooling gas is introduced to the rotor winding from below through the subslot. This kind of cooling is disclosed in the same paper in page 1937 viz. Figs. 4 and 5.

The combination of these two kinds of gas supply i.e. through the air gap and the subslot is also known and disclosed e.g. in British Patent No. 1,456,068 issued to the present applicant.

A common characteristic of the rotor windings cooled directly according to this preferred type of cooling lies in that during operation the temperature along each of the cooling channels is uniform and it is at most only a few degrees higher than that of the cooling air leaving the associated channel. For the sake of clarity in the following parts of the present specification the cooling system satisfying these criteria will be referred to as ones with "intensive direct conductor cooling".

In connection with the normal operation of turbo-alternators it is a well-known fact that depending on the variations of the mains load, on the type of the driving machines and on the kind of fuel used in the associated power plant, the momentary load of the turbo-alternator is fluctuating. When a high-speed turbo-alternator is installed, it is designed to a nominal load which corresponds to the maximum load to which it will be exposed. In many applications the maximum load occurs in only a fragment of the full working time, e.g. during 10–15% thereof. From this it follows that in such applications during a major portion of the operating time the use of a turbo-alternator with decreased loadability i.e. with smaller size and investment costs would be sufficient. When an air-cooled turbo-alternator designed for a given load is operated with a smaller load, the efficiency gets decreased due to the inevitable permanent losses that do not follow the decrease in the load.

In electrical networks the load peaks can be covered either by using machines designed for such peaks or by installing reserve machines which are operated only in the peak periods. In both cases turbo-alternators should be invested which can cover the full load.

The object of the invention is to provide a method and an arrangement which makes it possible that the loadability of high speed air-cooled turbo-alternators be adjustable and be flexibly adaptable to fluctuations of the actual load.

The invention is based on the recognition that in case of turbo-alternators having a rotor with intensive direct conductor cooling the temperature of the rotor winding which forms the limiting

parameter concerning loadability can be adjusted by changing the pressure of the cooling air. This is true because in such rotor the warming up of the rotor winding is practically identical with that of the cooling air and this latter is the function of the thermal capacity of the cooling air that streams through the rotor. It is also known that the thermal capacity of air is proportional with its pressure.

It is obvious that the ventillation and air-frictional losses of the turbo-alternator increase proportionally with the increase in air pressure. The calculated negative economic effect of such increase, however, especially in case of a turbo-alternator with rotor winding having an intensive direct conductor cooling and a combined air supply will be substantially less then the economic advantages coming from the possibility that the loadability becomes adjustable with the increase.

According to the invention a method has been provided for controlling the loadability of high speed air-cooled turbo-alternators, in which the rotor winding has an intensive direct conductor cooling and the method comprises the step of increasing the pressure of the cooling air up to about 2 bar abs. if the actual load increases. When the load decreases, the pressure is decreased accordingly, thus the pressure of the cooling air is controlled to correspond to the actual load.

In a preferable embodiment of the method the temperature of the rotor winding is measured and the pressure is controlled in such a way that this temperature remains constant within a tolerance range of $\pm 5°C$.

The temperature of the rotor winding can be determined by measuring the current flowing therethrough and the voltage drop.

Since the losses in the rotor are determined decisively by the Joule-losses, and the electrical resistance of the rotor winding in the operational temperature is known, it is sufficient to know either the current or the voltage for controlling the pressure of the cooling air so as to keep the conductor temperature constant. The control signal will then be proportional to the square of either one of these two quantities.

By using the method according to the invention it will be possible to install a turbo-alternator having a nominal loadability (in case of atmospheric pressure of the cooling air) which corresponds only to 70–80% of the peak load arising in the associated field of application. This possibility results in a substantial saving in investment costs compared to similar costs of a turbo-alternator designed for the peak load.

An arrangement has also been provided which is capable of carrying out the method, in which the turbo-alternator has a closed and sealed inner space, which is coupled to an air-recirculating cooling system that comprises an air supply with a compressor, an air-storage tank and according to the invention the arrangement comprises means capable of continuously changing the air-pressure in the inner space between about 1.01 and 2 bar abs.

The invention will now be described in connection with preferable embodiments thereof, in which reference will be made to the accompanying drawings.

In the drawings:

Figure 1 shows the schematic cross-sectional view of a rotor winding slot of a turbo-alternator with intensive direct conductor cooling (prior art),

Figure 2 shows the enlarged perspective view of a detail of the winding of Fig. 1 including a temperature distribution curve,

Figure 3 shows the block diagram of the arrangement according to the invention,

Figure 4 shows a series of diagrams illustrating the temperature changes of the rotor winding as a function of the loss-power dissipated in the winding, and

Figure 5 shows a further series of diagrams related to those of Fig. 4 showing the changes in efficiency as a function of actual load.

For understanding the method according to the invention the analysis of the heat transfer between the copper material forming the rotor winding of a turbo-alternator and the cooling air surrounding the copper has an outstanding significance. For this purpose in Fig. 1 the schematical sectional view of a portion of a rotor winding in a winding slot has been illustrated, in which an intensive direct conductor cooling is used and the winding consists of short cooling channels with combined air supply as disclosed in the British patent No. 1,456,068. The copper winding has turns separated by insulators and in every turn one or more cooling channels 1 is arranged extending in cross direction. Regarding the flow of the cooling air the cooling channels 1 are all connected in parallel and their inlets communicate with channel 2 located in the left side of the slot. The cooling air is supplied in the channel 2 both from above from the direction of air gap 3 and from below from subslot 4. The outlets of the cooling channels 1 are communicating with channel 5 arranged in the right side of the slot, and the warmed up air is discharged towards air gap 3. The flow of the cooling air is illustrated in Fig. 1 by arrows.

In the case of a pure gap pick-up cooling the lower air supply is missing, while in the case of a pure subslot cooling the upper supply is missing.

Fig. 2 shows a portion of the winding, in which the dashed line illustrates one of the cooling channels 1 and the parallelpiped drafted around it by full line designates the copper volume cooled by the illustrated cooling channel 1. The diagram directly above the cooling channel shows the change of the temperature of the cooling air Δt_g and of th cooper Δt_r along the channel 1.

Since the copper is a very good heat conductor, its temperature along the short cooling channel 1 is constant or it can be considered to be constant due to the intensive conductive heat flow in the copper. The inflowing cooling air warms up in the cooling channel 1 and when it leaves the channel 1, its temperature is only slightly lower than that of the copper. In the end of the channel 1 the temperature of the air is increased by a value of Δt_{gm} and the temperature of the cooper is higher by a value of Δt_{rm} than that of the inflowing air.

Although the copper can be cooled in several other ways than illustrated in the drawing, the use of the method according to the invention requires such a cooling, in which the temperature of the copper is substantially constant along the cooling channels, i.e. it is at most within a tolerance range of $\pm 5°C$ and this temperature is practically identical with the temperature of the outflowing air i.e. it is at most by about 10°C warmer than the air. These are the characteristics of the previously defined intensive direct conductor cooling systems. For decreasing the frictional losses the rotors of the turbo-alternators which have intensive direct conductor cooling are designed generally with increased length and smaller diameter, in which the length-to-diameter ratio of typically between about 3 and 5.

Reference is made now to Fig. 3 which shows the schematic block diagram of an arrangement capable of carrying out the method according to the invention. A turbo-alternator 10 which has a rotor with intensive direct conductor coling is equipped with heat exchangers 11 and 12 that comprise inlet 13 and outlet 14 coupled to a cooling water circulating apparatus, not shown in the drawing. The end portions of the rotor of the turbo-alternator 10 are extending out of the constructional housing and they are provided with sealings 15, 16 which can be made of conventional shaft seals with oil lubrication used generally for turbo-alternators with hydrogen cooling or of dry shaft seals comprising, e.g. carbon rings.

A conduit 17 is coupled to the cooling system which is connected through pressure regulating valves 18 and 19 to air tank 20. From the free space air can be fed in the air tank 20 through filter 21, a pair of parallel compressors 22, 23 and a drier 24.

The pressure in the air tank 20 is typically about 10 bar which is measured and displayed by pressure meter 25. The pressure prevailing in the conduit 17 which is equal to the internal pressure of the turbo-alternator 10 is measured by pressure meter 26. Magnetic ventil 27 serves to switch the pressure regulating valve 18. By means of the pressure regulating valves 18 and 19 the pressure in the turbo-alternator can be controlled continuously between about 1.01 and 2 bar. The adjustment can be actuated either by hand or by means of an appropriate automatic control.

For the sake of better orientation the instruments used for measuring and displaying the operational parameters of the turbo-alternator 10 have not been shown in Fig. 3.

The novel character of the arrangement shown in Fig. 3 lies in that the air pressure prevailing in the interior of the high-power turbo-alternator 10 can be changed continuously from the normal atmospheric value up to about 2 bars and any set pressure value can also be maintained, if required.

It has already been pointed out that owing to the comparatively small rotor diameter the air frictional losses of the turbo-alterntor 10 are on a rather low level. This fact and the uniform and adjustable copper temperature due to the intensive direct conductor cooling made it reasonable to increase the operational air pressure in order to increase the loadability. In the following discussion, based on actual sets of measurements, various important characteristics of the turbo-alternator 10 will be shown in case of different pressures of the cooling air.

The measurements were carried out by an air cooled turbo-alternator 10 with a nominal loadability of 75 MVA, and for obtaining comparable results the measurements were also carried out by using three other turbo-alternators of 80 MVA and designed for hydrogen cooling and having the same size and internal structure as the first machine, and in the measurements air was used as cooling medium instead of hydrogen. The pressure was changed in the range of 1 and 2.2 bar in about 50 settings. The detailed analysis of the test results has shown that the conductor temperature-increases obtained in the different machines were practically the same, which provided the possibility of drafting relationships of more general character.

It has been experienced that in case of air cooling the loadability of the machine is decisively limited and defined by the temperature rise of the rotor winding.

With these machines, taking all load points into consideration, the temperature rise of the rotor can be expressed by the following relationship:

$$\Delta t_r = 6 + \frac{0.017}{p}\left(P_{Fe} + P_z\right) + \frac{0.25}{p^{0.92}} \times P_r$$

where: p —the absolute air pressure (bar)
P_{Fe}—the iron loss (kW)
P_z —the short-circuit loss (kW)
P_r —the copper loss of the rotor (kW)

The diagrams of Fig. 4 shows the temperature rise of the rotor winding as a function of the loss generated in it at different air pressures, at rated voltages of the machine (at constant iron losses) with a deviation of a few centegrades due to the varying short-circuit loss. As a point of interest and for guidance the figure shows also the temperature rise of the rotors measured in hydrogen of different purities (area with hatched line).

In the case of 75 MVA load of the machines and cos φ = 0.85 depending on the temperature of the cold cooling air and on the air pressure, the rotor loss in operation varies between about 230 and 250 kW. It can be seen in the figure that in case of increasing the air pressure by 25% the rotor loss can also be increased by approx. 25% at the same temperature rise. This 25% increase of the loss corresponds, in turn, to approx. 12% increase of the field current and to about 20% of the output, that is to say, the 75 MVA machine can be loaded with approx. 90 MVA (with unchanged temperature rise of the rotor winding).

As Fig. 4 shows, the loadability of the machine can be increased further by increasing the pressure of the air (up to approx. 100 MVA at 1.5 bar abs.). The stator winding, built in accordance with the output corresponding to hydrogen cooling, would offer a possibility for that. However, the heating (in operation near to cos φ = 1) of the laminated stator core end parts cannot be influenced by the air pressure to the same extent as that of the rotor winding. Due to the air friction losses, increasing in proportion to the air pressure, the gradual deterioration of the efficiency imposes practical limits to the increase of the air pressure.

These phenomena are illustrated in the curves of Fig. 5. Curve *a* shows the efficiency of the examined type at 1 bar abs. pressure, while curve *b* shows it at 1.25 bar abs., finnally curve *c* shows the same at 1.5 bar abs. air pressure. Due to the phenomena experienced at the core ends the loadability determined by the rotor winding being 90 MVA at 1.25 bar abs. and 100 MVA at 1.5 bar abs. has been limited to 88 MVA and 95 MVA, respectively.

At a continuous control of the pressure of the air, filling out the internal part of the machine, as a function of the load, curve *d* plotted by the dash-dot line gives the resultant efficiency in the output range above 75 MVA.

It should be noted that the diameter of the rotor of the examined turbo-alternator was 930 mm and its length was 2850 mm. Curves *e* and *f* of Fig. 5 show the efficiency characteristics of two other and different turbo-alternators both designed for 95 MVA rated output in the case of atmospheric air pressure. In the case of curve *e* the rotor had a diameter of 930 mm and a length of 3700 mm, while in the case of curve *f* the diameter was 1000 mm and the length was 3250 mm. In both cases the rotor mass was practically the same.

From the comparison of the efficiencies associated with common loads, i.e. from the comparison of curves *a* and *d*, as well as of *e*, it can be seen that regarding the resulting operational efficiency the decisive factor lies in that in a given operational period (e.g. in a year) how long and under what load the actual operation takes place. If in the dominant part of the working time (e.g. in 90% of all times) the load is 75 MVA and the peak load of 95 MVA occurs only rarely, than even the resulting efficiency of the type operating with increased air pressure is more favourable than that of the other types. Up to a load of 95 MVA the efficiency of the machine with increased rotor diameter and shorter rotor (associated with curve *f*) is smaller than that of the other machine designed for 75 MVA.

This comparison does not take into account, that the investment costs of a machine designed for a load of 95 MVA are substantially higher than similar costs of a machine designed for 75 MVA.

It can therefore be seen that by increasing the air pressure in the turbo-alternator, the loadability of a machine, designed for a given load, can be increased, whereby the temporary load peaks can be covered without the need of installing further machines or more expensive machines designed for the load peaks.

It is considered that the use of turbo-alternators designed to outputs of 70–80% of the load peaks can be justified and are preferable if controlled according to the present invention.

Compared to conventional air-cooled turbo-alternators substantial advantages arise from the fact that within the controlled range the rotor temperature is constant (independent from the actual load). This property eliminates any problem that would result from the different thermal

dilatation of iron and copper. A further advantage comes from recirculating the cooling air in a closed system because in this way the humidity of the air can be kept in a desired range. It is known that high humidity decreases the life expectancy and reliability of turbo-alternators, which can thus be eliminated.

The pressure of the cooling-air can be controlled by the arrangement according to the invention either on the basis of the resistance of the rotor winding or from the knowledge of the characteristic curves of the machine on the basis of measuring the rotor losses. The temperature of the rotor winding can be determined from the rotor resistance, and when the load increases or decreases, the pressure should be changed in such a way that the winding has a constant temperature.

The rotor loss can be determined on the basis of the rotor voltage or of the rotor current.

The control can be manual, however, the clear conditions for adjusting the pressure enable the use of an automated control, too.

CLAIMS

1. A method for controlling the loadability of high speed air-cooled turbo-alternators, in which the rotor winding has an intensive direct conductor cooling, and the method comprises the step of increasing the pressure of the cooling air up to about 2 bar abs. if the actual load increases.

2. A method as claimed in claim 1, wherein the temperature of the rotor winding is measured and during the pressure adjusting step this temperature is kept within a tolerance range of at most $\pm 5°C$.

3. A method as claimed in claim 2, in which the temperature of the rotor winding is measured on the basis of measuring the rotor current and the voltage drop on the rotor winding.

4. A method as claimed in claim 2, in which the adjustment based on the temperature measurement of the rotor winding is carried out on the basis of the square of the measured value either of the rotor current or voltage.

5. A method as claimed in claim 1, in which the turbo-alternator is designed to bear a load corresponding to about 70 to 80% of the peak load occurring in the location where said turbo-alternator is installed.

6. An arrangement for carrying out the method as claimed in claim 1, wherein the turbo-alternator comprises an interior which is sealed and closed from the free atmosphere and the arrangement comprises an air-cooling means circulating air in a closed loop, the air-cooling means being coupled to said interior, and an air-supply means including a compressor and an air tank, wherein there is a means for continuously adjusting the air-pressure in the interior within a pressure range of about 1.01 and 2 bar abs.

7. An arrangement as claimed in claim 6, comprising a means for measuring the air pressure in the interior and a means for detecting the electrical resistance of the rotor winding by sensing the temperature thereof.

8. An arrangement as claimed in claim 7, in which the pressure adjusting means adjusts the pressure in accordance with any change in the actual load by maintaining the temperature of the rotor winding contant during adjustment.

9. An arrangement as claimed in claim 6, comprising a drier adjusting the humidity of the air fed into the air tank to a predetermined constant value.

10. A method for controlling the loadability of high speed air-cooled turbo-alternators substantially as herein described with reference to the accompanying drawings.

11. An arrangement for controlling the loadability of high speed air-cooled turbo-alternators substantially as herein described with reference to Figs. 1, 2 and 3.

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